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The generation of residual biomass during the production of bio-ethanol from sugarcane, its characterization and its use in energy production

Waldir Antonio Bizzo *, Paulo César Lenço [1], Danilo José Carvalho, João Paulo Soto Veiga [2]

Faculty of Mechanical Engineering, University of Campinas – UNICAMP, 13083-970 Campinas, SP, Brazil

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ABSTRACT

Sugarcane bagasse is the residue produced by mills after juice is extracted from sugarcane. Other important solid residues in the sugarcane-to-sugar-and-ethanol production chain are the leaves and tops of the stalks (together referred to as cane trash). Although it represents a significant portion of the energy in sugarcane, cane trash is currently left in the fields. This paper has described and analyzed how residues (bagasse and cane trash) are produced from sugarcane and their use as an energy source in the production of ethanol. Also, it presents a review of the physical properties and characteristics of bagasse and cane trash and estimate their energy potential. Bagasse and cane trash have similar fuel characteristics to other biomasses fuels. Special attention should be given to the characteristics of cane trash ash, which has higher fusibility and alkali levels than bagasse. A flowchart of a typical mill was described and the thermal and mechanical energy consumption at various stages of the production process was determined. Of the energy consumed as work, about 58% is accounted for by milling and juice extraction, and 33% by the generation of electricity for use in the plant. In a typical mill using steam generators operating at average pressure and temperature (22 bar, 300–360 °C), about 15% of the bagasse produced is surplus, and an average of 480 kg of steam is used per tonne of cane processed. An energy consumption analysis revealed that there was significant scope for reducing the amount of steam needed to operate the turbines in mills because of the low isentropic efficiencies identified. Cane trash, which is not yet used for energy production, also shows great energy potential because it is produced in similar quantities to bagasse, and its calorific value is only slightly lower.

Contents

* Corresponding author. Tel.: +55 19 3521 3373; fax: +55 19 3289 3722.
E-mail addresses: bizzo@fem.unicamp.br, waldirbizzo@gmail.com (W. Antonio Bizzo), lenco@actualis.com.br (P.C. Lenço), liar@fem.unicamp.br (D.J. Carvalho), jpsveiga@usp.br (J.P.S. Veiga).
[1] Present adress: University of Cuiabá, Cuiabá, MT, Brazil.
[2] Present adress: Luiz de Queiroz College of Agriculture, University of São Paulo, Piracicaba, SP, Brazil.

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1. Introduction

Sugarcane bagasse is the residue produced by mills after juice is extracted from sugarcane. Over the years bagasse has ceased to be a residue and has become an important energy source, making a knowledge of its properties and characteristics important so that it can be used efficiently in steam generation, gasification, pyrolysis or even as raw material for acidic or enzymatic hydrolysis.

Sugarcane bagasse is traditionally used to generate the steam needed in sugar mills and in ethanol distillation. The Pro-Alcohol program, which began in Brazil in the '70s, was the first major program to replace fossil fuels with a renewable source (hydrous ethanol). At that time bagasse was considered a residue and, as such, needed to be disposed of, which was done by burning it in boilers, thereby generating part of the electricity used by the production mill. Steam was, and still is, expanded in back-pressure turbines to generate electricity to drive the milling tandems and large pumps. Steam from the exhaust turbines is used in the sugar and alcohol production process. Not all plants were able to meet all their own electricity needs because up to the mid '80s electricity production in Brazil was fairly inexpensive and generating capacity far exceeded demand.

From the '90s the cost of electricity began to rise, and mills began to generate increasing quantities of electrical energy until they became self-sufficient, mainly by using steam to generate electricity [1]. Thus, over the past 40 years bagasse has gone from being an unwanted residue to representing an important source of energy, and its importance continues to increase as energy prices on the international market rise.

In the past 30 years, with the increasing demand for and rising costs of electricity, the oil crisis and the possibility of a renewable fuel with lower CO_2 emissions than fossil fuels, there has been renewed interest in the sugar/alcohol industry, and efforts have been made to increase its efficiency so that surplus electricity can be sold. Indeed, this is already happening in some Brazilian sugar and ethanol mills.

Other important solid residues in the sugarcane-to-sugar-and-ethanol production chain are the leaves and tops of the stalks (together referred to as cane trash). Until the '90s, sugarcane trash in Brazil was burned in the fields before the harvest to make cutting the cane and manual harvesting easier. Mechanized sugarcane harvesting was first introduced in the late '90s and has been growing gradually since then, to the point where it now accounts for about 55% of sugarcane production in the state of São Paulo, the largest sugarcane-producing region. Although it represents a significant portion of the energy in sugarcane, cane trash is currently left in the fields.

The search for increased energy efficiency in sugar and alcohol mills is still in its infancy, and much remains to be done to harness the energy from sugarcane bagasse. A knowledge of the characteristics and physical properties of bagasse is essential for the development of any process or equipment using this residue.

The objective of this paper is to review the physical properties and characteristics of the solid residues generated during the production of ethanol from sugarcane (bagasse and cane trash), to evaluate the different ways in which the energy from these residues is used and to estimate their energy potential.

Table 1
Production of sugarcane and sugarcane products in Brazil [4].

Harvest	Sugarcane (tonne)	Ethanol (m³)	Sugar (tonne)
2007/08	495,843,192	22,445,979	31,297,619
2008/09	563,638,524	27,582,737	31,335,830
2009/10	602,254,167	25,714,732	33,068,261

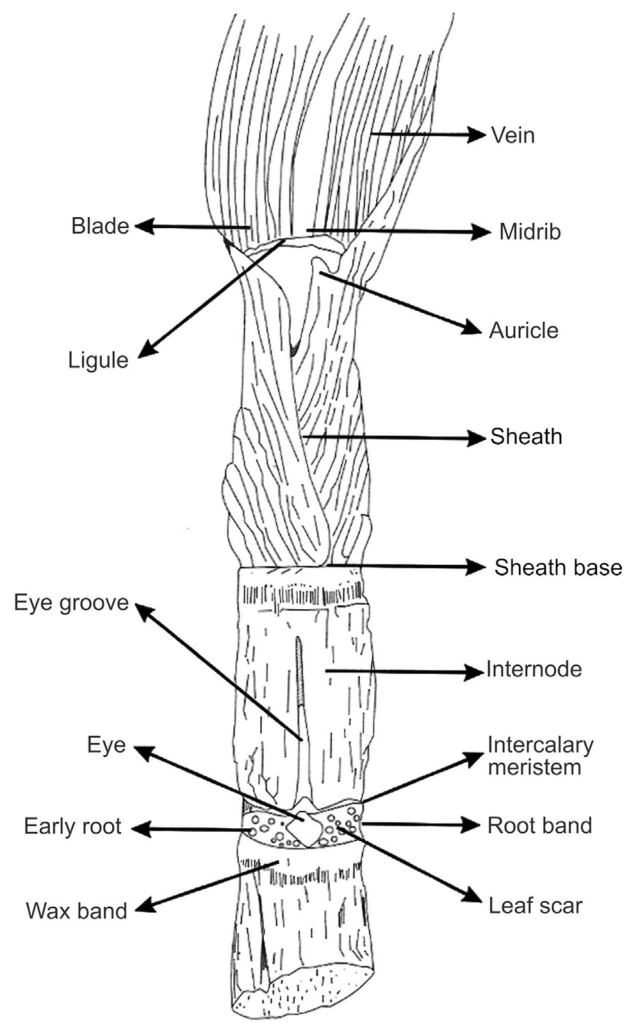

Fig. 1. Structure of a sugarcane leaf [7].

2. Methodologies

A literature review covering the outcomes of physical and chemical analysis of sugarcane residues (bagasse and cane trash) was undertaken to characterize their physical properties. Samples of sugarcane bagasse and cane trash were obtained from two medium-sized mills located in the state of São Paulo. Their properties were determined and compared with the results of prior studies. The analytical methods used are described, and the results of the various studies are compared.

Technical visits were made to conventional medium-sized mills (with typical production of 600 m^3 of ethanol/day) to investigate the different ways in which energy was being used. A process flow chart was compiled from the information gathered in the field and from an analysis of a typical design of a sugarcane-to-ethanol plant. The same was done for the system for producing steam and electricity. Using this information a mass and energy balance was established for a medium-sized mill.

3. Morphology of sugarcane

In Brazil, sugarcane was first cultivated in the 16 century by Martim Afonso de Sousa, the Portuguese explorer, who introduced it to the region now known as São Paulo. From 1500 to 1600, sugarcane spread throughout the Americas, and Brazil was one of the first countries to introduce it for commercial purposes [2].

Today, sugarcane is grown in almost every Brazilian state. The state of São Paulo is the largest producer, accounting for about 60% of national production, and is followed by the states of Paraná, Minas Gerais, Pernambuco, Alagoas, Mato Grosso and Mato Grosso do Sul, according to data published by the Ministry of Agriculture National Sugarcane and Agro-Energy Audit [3]. Table 1 shows data on sugarcane, sugar and ethanol production.

Sugarcane (*Saccharum officinarum*) has been known to man since 8000 BC and is one of six species from genus *Saccharum*, tall grasses indigenous to South and Southeast Asia. It is a complex hybrid found in tropical and subtropical regions [5] and has a root system, stalks, leaves and efflorescence. The mature stalks have the most industrial value because they are used to produce both juice and bagasse [5]. However, cane trash can play an important role in energy generation or biofuel production [6]. Fig. 1 shows a diagram of the structure of a sugarcane leaf.

Sugarcane stalks are cylindrical, straight, fibrous and rich in sugar. Fig. 2 shows a cross-section of a stalk in the internodal region. The outer part is bark, and the typical colors of the stalk are produced by pigments in the outermost cells of the epidermis. The cortex is composed of several layers of thick-walled lignified cells, which give strength and protection to the internal tissues, commonly known as fibers. These are formed of vascular vessels and the fundamental tissue or parenchyma, known as pith. The pith consists of short, loose cells, all of whose dimensions are nearly identical as they are isodiametric [5,8].

Sugarcane is composed of juice (approximately 86–92%) and water-insoluble fibrous materials (from 8% to 14%) [2]. Typical mass balance values adopted in Brazil for sugar and alcohol production indicate a fiber content varying between 11% and 13% depending on when the cane is harvested.

The composition of sugarcane arriving at a mill depends on several factors, such as the variety, the amount of tops and leaves, the ripeness, when the cane was harvested, if the leaves were burned before harvesting, whether mechanized or manual harvesting was used and climatic factors (primarily rainfall). Table 2 shows the typical composition of sugarcane in some countries where this crop is grown.

The percentage weight/weight of solids in a sucrose solution, i.e., the sucrose content of a solution, is expressed in degrees Brix [10]. Pol, or polarization, represents the percentage of sucrose in a sugar solution determined using a method based on the ability of sugar to deflect polarized light [11].

The juice from sugarcane is composed of water (70–73%) and solids (27–30%). The solids consist of fibers and soluble solids, the latter accounting for 13–18% of the total. In addition to sucrose (sugar), the juice contains other residual elements, such as fats, waxes, amino acids and mineral salts [2].

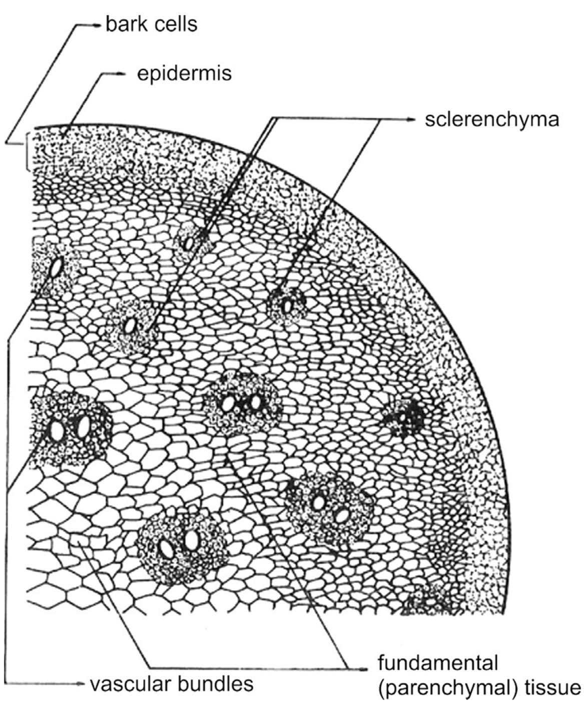

Fig. 2. Cross section of an internode [5].

4. The harvesting process and cane trash production

The leaves of the sugarcane plant are responsible for the interaction between the plant and the atmosphere and perform photosynthesis to provide energy for the plant [12]. Fig. 3 shows a diagram of the leaf structure. Planting sugarcane involves laying cane sections horizontally in furrows so that there is an average of 12 buds per linear meter. Typically, four to five successive harvests

Table 2
Typical average composition of cane (in kg/100 kg cane) in different countries [9].

	Brazil	Australia	South Africa	Colombia	Philippines	Mauritius Islands	Louisiana (USA)
Pol	14	14.6	12.8	13.2	10	12	14
Brix	16.2	16.4	15	15	12.5	13.8	16
Water	70.5	69.3	70	70	72.5	71.2	71
Fiber	13.3	14.3	15	15	15	15	13

are required; the first usually takes place 18 months after planting, and subsequent harvests take place every 12 months. After five or six harvests on average, the plants are removed because of their reduced productivity and new sugarcane or other crops are planted.

Although sugarcane is produced on a large scale, manual cutting is still widespread, so leaves must be burnt in the field beforehand to make cutting and harvesting easier. However, the environmental pressure to eliminate this practice and the decreasing cost of mechanized harvesting has led to this type of harvesting being adopted instead of manual cutting [13]. Mechanical harvesting is now in widespread use and in the 2010/2011 harvest season accounted for 55% of the sugarcane harvested in the state of São Paulo [14].

In mechanized harvesting, the harvester performs the following operations [15]:

– the tops and the greenest leaves are cut (topping);
– the rows are separated, and stalks that have fallen down are lifted and pushed forward and down for cutting;
– the base of the plant is cut using two cutting disks with blades at ground level (base cutter);
– the complete stalks are transported to the chopper;
– the stalks are cut into billets approximately 0.3 m long in the chopper;
– the cane trash and leaves mixed with the billets are removed in the primary extractor just above the chopper;
– the elevator (conveyor belt) raises the billets so they can be dropped inside the collection vehicle;
– the secondary extractor removes any further cane trash and leaves at the end of the elevator.

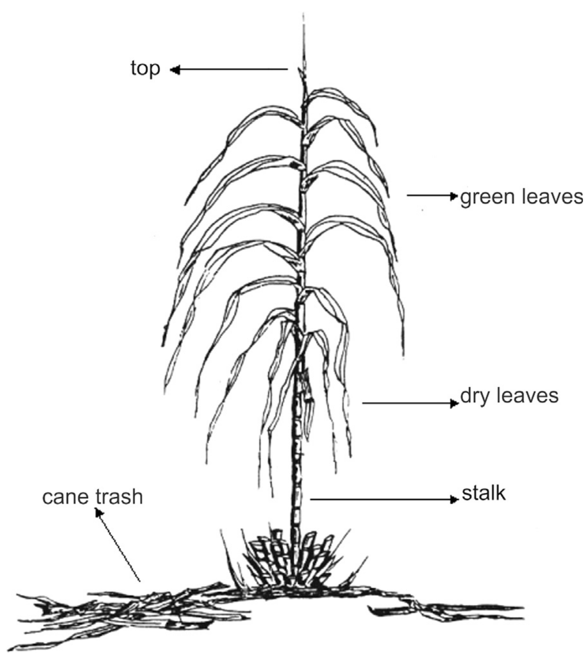

Fig. 3. A sugarcane plant showing the leaves and stalk and the cane trash on the ground [58].

Fig. 4 shows a diagram of a sugarcane harvester.

At the end of the process, the billets are taken for processing (about 5% of the load consists of other parts of the cane as well as earth) and the material separated by the extractors is released on the ground, forming a layer of residue known as cane trash, which consists of wet leaves, dry leaves and the tops of canes. The residue may also contain fractions of stalks, roots accidentally pulled out during the cutting process and weeds [20]. The moisture content of the material left in the field is in the order of 50% according to average figures reported by various authors Braunbeck et al. [13,16], Ripoli et al [17–20], Hassuani et al. [21], Sartori [22], Scarpari and Beauclair [12]. This figure falls by 30% after two to three days and drops to 15% fifteen days after the harvest [21]. Because of the large energy potential of cane trash, various techniques for gathering and transporting this residue have been studied. The average productivity of sugarcane in the state of São Paulo is 85 t.ha^{-1}.year^{-1} (wet basis) [4]. Each tonne of stalks produces about 125 kg of bagasse (dry basis) and 140 kg of cane trash (dry basis) [17–20]. Typical moisture content of bagasse coming to the boilers is 50% (wet basis).

5. The milling process and bagasse production

Bagasse is a by-product of the process in which raw juice, which contains sucrose, is produced from sugarcane. The juice can be used to produce sugar in a concentration process or ethanol by fermentation followed by distillation.

The production of sugarcane juice involves two basic processes: preparation of the cane and extraction of the juice. Two different techniques can be used to extract the juice: milling or diffusion. Each technique results in sugarcane bagasse with slightly different characteristics.

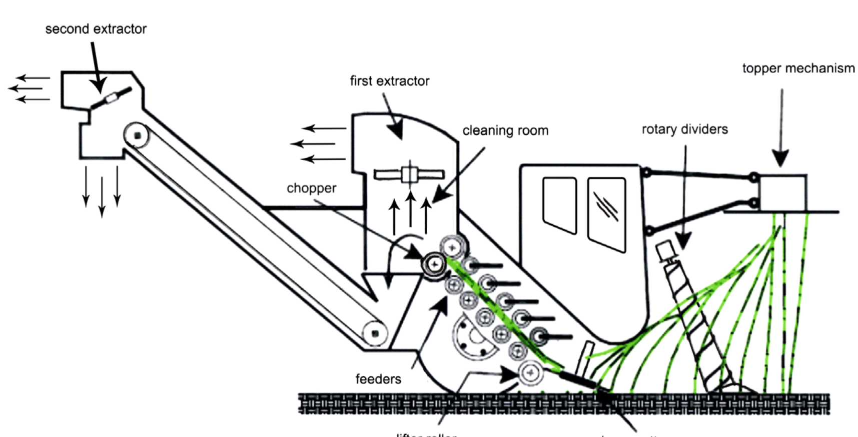

Fig. 4. Diagram of a sugarcane harvester.
(*Source*: Braunbeck, Magalhães and Garcia [16]).

5.1. Preparation of sugarcane

The stalks are cut to the appropriate size so that they can be used to feed the milling tandem and subsequent raw-juice extraction process [9]. The efficiency of the extraction process is highly dependent on the way the cane has been prepared, which usually involves the use of blades and rotary hammers to cut and shred the stalks.

The main objectives of the preparation process are to make the stalks smaller, rupture cells containing sucrose and produce material with characteristics suitable for extraction by milling or diffusion. The preparation required for diffusion and milling is similar, both processes requiring that the stalks be cut into small pieces to allow the juice to be extracted while at the same time retaining the characteristics needed to allow them to be fed into the milling tandem or compressed on the diffuser bed. Optimal preparation not only results in the cells being ruptured, but also preserves any long fibers so that raw juice can be extracted during diffusion or milling [9]. The aim when preparing sugarcane is therefore to make it as easy as possible to extract the juice (sucrose) in the stalk cells. To achieve this, the cells containing sucrose must be ruptured to increase the extraction efficiency of the milling tandem or diffusers. A typical preparation, or open-cell, index in standard tests is around 90% of the cane entering the milling process; however, these rates can be expected to be higher for diffusion extraction [1].

Rotating blades and shredders are the most frequently used devices to prepare sugarcane as the blades produce a cane bed with almost uniform thickness and the shredders completely destroy the cane structure, producing a large number of open cells from which juice can then be extracted. To achieve a 1% increase in the amount of sugarcane juice extracted in a mill, a 4% increase in cane preparation is needed, i.e., the number of open cells must be increased by 4% [8].

5.2. Extraction of raw juice by milling

The purpose of sugarcane milling is to extract the sucrose in the cane by compressing the fibrous part of the plant (the stalk). The extraction rate is expressed as a percentage and is defined as the ratio of extracted sucrose to total sucrose in the sugarcane [9].

After the cane has been prepared, it passes through the milling equipment or "milling tandem", which is typically composed of a set of four to seven three-roll mills (sets of three cylinders with radial grooves arranged at the center in the form of an isosceles triangle) to crush and remove the juice from the cane. The two bottom rollers have their axes fixed and rotate in the same direction, while the moveable upper roller rotates in the opposite direction to the lower axes. The position of the upper roller is hydraulically controlled to maintain the crushing pressure (Fig. 5).

Three-roll mills typically have three cylinders but may also have one or two auxiliary cylinders, with diameters smaller than those of the crushing cylinders. The auxiliary cylinders compress the bed formed by the fibers, thereby increasing extraction efficiency [8,1]. To increase feed capacity and drainage, the cylinders have grooves, which influence the shape of the resulting bagasse. These follow the circumference of the cylinder, are V-shaped and form a 30–35° angle. This angle may be as large as 45° when there is a possibility of damage from stones or pieces of metal. The spacing between grooves varies from 12.5 to 25 mm [8]. In more recent models the spacing ranges from 25 to 75 mm, with a spacing of 50 mm and groove angle of 40–50° being the most common [9].

To increase the amount of sucrose extracted, water is added to the sugarcane during the milling process. This is called imbibition, as when it leaves the three-roll mill the bagasse still retains some juice either as a result of capillary action or because some cells were not fully crushed [1]. There are three types of imbibition: simple, compound and mixed (Fig. 6). Simple imbibition involves soaking the bagasse with water after each three-roll mill. The resulting juice goes straight to the manufacturing process. In compound imbibition, water is applied only in the last three-roll mill in the milling tandem, and the diluted juice is wholly or partly returned to the front of the previous three-roll mill; the juice for processing is extracted in the first and second three-roll mills. Mixed imbibition, as the name suggests, combines simple and compound imbibition: water is applied in more than one three-roll mill, and juice from each intermediate mill is partially

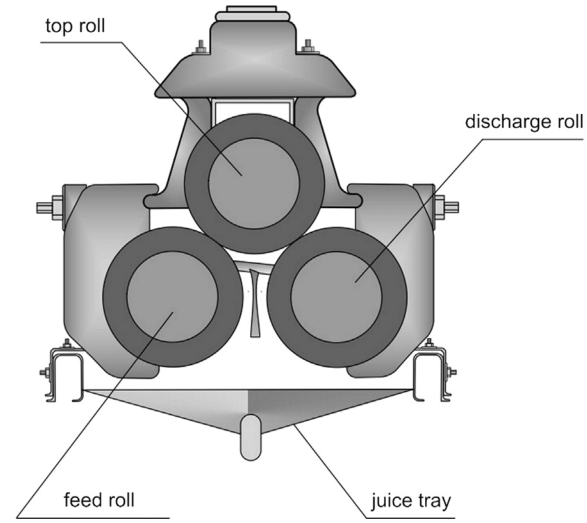

Fig. 5. Diagram showing a classic three-roll mill arrangement. (adapted from Rein [9]).

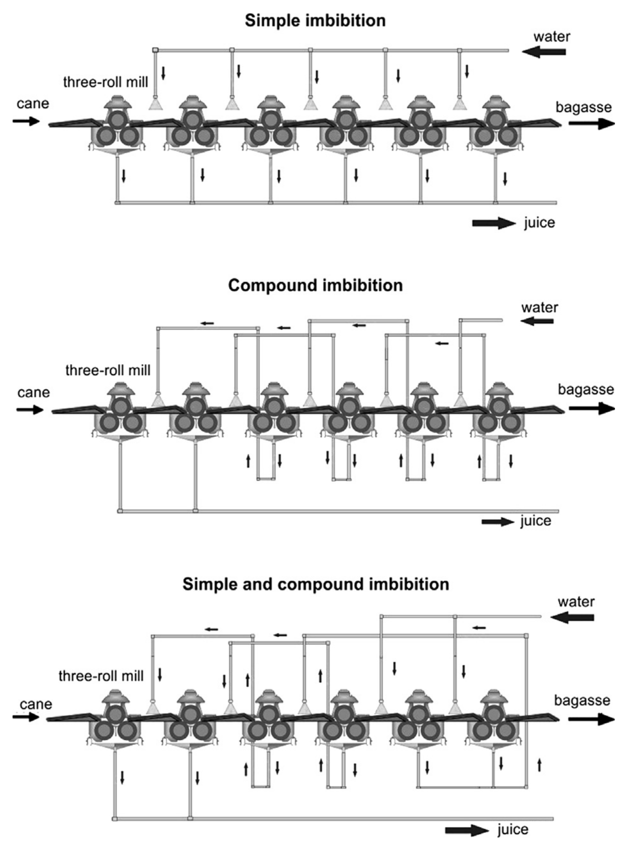

Fig. 6. The three types of imbibition used to extract sugarcane juice.

returned to the previous mill [1]. Fig. 6 shows the three types of imbibition used to extract raw sugarcane juice.

Payne (1990) states that bagasse can absorb up to 650% of its mass in liquid but that maximum extraction occurs when the liquid absorbed corresponds to 250% of the mass of the fiber. According to the same author (1990) [8], to improve the efficiency of sucrose extraction the imbibition water must be applied at the highest possible temperature. Typical temperatures range from 70 °C to 80 °C and are limited by potential feeding problems because the fiber becomes plastic at high temperatures, making it very slippery. The use of hot water, however, can have undesirable effects on the extraction process, such as early flocculation of proteinaceous material and increased dissolution of impurities in the juice [1]. There is no consensus in the literature surveyed regarding the most suitable temperature for imbibition water or the most appropriate imbibition arrangements (simple, compound or mixed). The extent to which water can be added to increase the amount of juice, and therefore sucrose, extracted is limited by factors such as the evaporative capacity in the extraction process. Although, like many biomasses, bagasse is hygroscopic and retains moisture in the fiber interstices, the moisture content at the end of the milling process is around 48–52%, as the three-roll mills are able to remove much of the water added by imbibition during milling.

5.3. Extraction of raw juice by diffusion

Diffusion is a phenomenon in which the concentrations of two solutions of initially different concentrations separated by a permeable or porous membrane equalize over time. When raw juice is extracted from sugarcane, parenchyma cells act as a semipermeable wall, and the sucrose contained in the cells is extracted by a process in which a fluid (water and diluted juice) flows through a porous bed formed by the shredded cane. In solid–liquid extraction a portion of the juice is extracted through a leaching process. The remainder of the juice contained in the whole cells and small capillaries within the particles is extracted in a physical and chemical exchange caused by the difference in osmotic pressure and molecular diffusion between the juice inside the cells and the extraction fluid [1].

The most commonly used diffusers are percolation diffusers, in which the water and hot juice are recirculated in the opposite direction to the direction in which the shredded stalks move. There are various types of percolation diffusers; some are U-shaped or even inclined, but the most widely used is the horizontal bed, which consists of a tunnel open at both ends. The base is made of perforated plates, and the shredded cane bed is dragged along a conveyor in the opposite direction to the diffuser fluid (water and diluted juice). Fig. 7 shows a schematic representation of a diffuser used to extract sugarcane juice.

For diffusion to occur in the juice extractor, the bed must be compact and permeable, the cell rupture index must be in the order of 94% and the fibers must have been shredded as little as possible so that they are around 10–15 cm long [9]. After passing through the diffusion system, the bagasse is subjected to a water-removal process, as the moisture content of bagasse from a diffuser can be up to two and a half times that of bagasse from a milling system [9]. The most common method of extracting the excess moisture is to use three-roll mills similar to a tandem mill. The temperature of the extraction water in the diffusion vat is normally around 70–75 °C. The bagasse therefore leaves the diffuser at the same temperature and is more plastic and slippery, with a lower coefficient of friction, making it more difficult to remove the water. Payne [8] recommends the use of screw presses, while Rein [9] states that draining is faster in three-roll mills and that innovations, such as those developed in Brazil, that combine the grooves in the three-roll mills with transverse holes between the grooves further improve drainage.

Factors that must be controlled because they affect the diffusion process and the structure of the bagasse include:

- Particle size. This is highly dependent on the extent to which the cane has been prepared. In diffusion, unlike in milling, bagasse particles do not suffer mechanical deformation when the juice is being extracted. The shape, size and stiffness of the particles have a direct influence on how the extraction liquid is distributed through the cane bed (the percolation rate) and will subsequently influence how the bagasse is used as fuel.
- Extraction temperature. This has a direct impact on energy consumption. While the average temperature used (75 °C) implies additional energy consumption, it has the advantage that it reduces the viscosity of the leaching liquid as well as microbiological and enzymatic activity. However, excessively high temperatures cause thermal degradation and reduce extraction efficiency.

In places such as South Africa, Central America, Europe and Egypt, the diffusion method is used to extract juice from sugar beet and sugarcane. In Brazil, however, this technique is not in widespread use [1]. In 2004, only 8 out of a total of 347 mills used

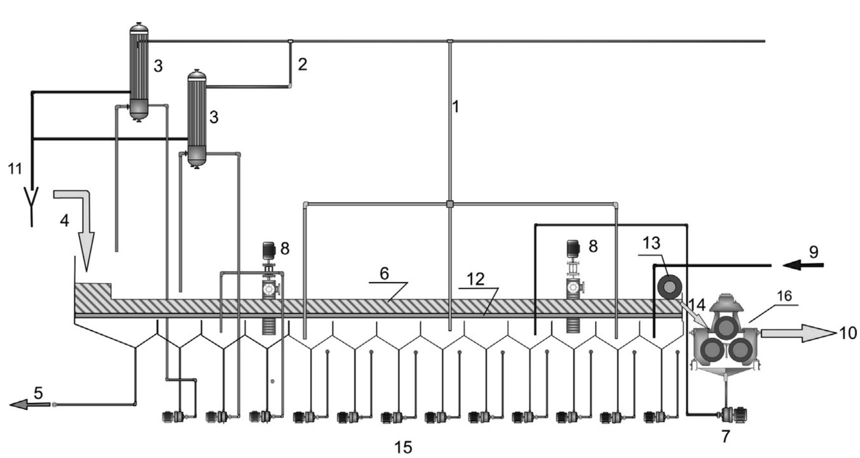

Fig. 7. A sugarcane diffuser. (Adapted from Rein [9]).

diffusers, while according to data supplied by manufacturers, the corresponding figure for 2008 was 22 (out of a total of 393 mills in operation or under construction) [23]. Because this, little is known about the performance as fuel of the bagasse produced by diffusers. The larger amount of long fibers in the bagasse produced by diffusers, as indicated in Fig. 10, does not seem to affect the combustion process in boilers. Almost boilers in sugarcane mills uses grate firing in the combustion chamber. A possible characteristic would be a different composition of bagasse ashes produced by diffusion, when compared with the bagasse produced by mills. The intensive process of leaching can extract some portion of metal oxides. We are not aware of any study on this subject.

6. Characterization of bagasse and cane trash as fuel

Sugarcane bagasse consists of clusters of particles of different shapes and sizes. Because of the different shapes, storage characteristics (compression) and moisture content of these particles, bagasse forms irregularly shaped clusters varying in size from a few millimeters to a few centimeters. However, although these clusters have low mechanical strength, they make handling and transporting bagasse difficult, particularly in the feeding mechanisms of gasifiers and boilers.

6.1. *The morphology of bagasse Particles*

Nebra [24] observed two very distinct groups of bagasse particles, regardless of the extraction process used: larger particles in the form of rods, commonly called fibers, and smaller, slightly rounded particles, called pith. Both are very porous and hygroscopic and vary in size. Fig. 8 shows a representation of these particles and of a cluster formed of fibers and pith. After sieving bagasse, Nebra and Macedo [25] found that both fibers and pith typically had a cylindrical shape. Fibers have high height-to-ellipsoid-base (Lp/ap) ratios, while pith particles have high base-to-height (ap/Lp)ratios, as shown in Fig. 9.

Arnao [26] used sieves to compare bagasse produced by diffusion and bagasse produced by milling and found that both had approximately the same distribution of fibers (72%) and pith (28%). The complete particle size distribution is shown in Fig. 10. It can be seen that larger particles (average diameter greater than 5 mm) predominate in bagasse from a diffuser, whereas particles with a diameter of 1.4 mm predominate in bagasse from mills.

The use of sieves to characterize the geometry of bagasse particles may yield unrepresentative results because of the great diversity of the shape and size of these particles [26].

In this type of study it is very difficult to homogenize sugarcane bagasse and characterize it. Shape and size are inseparable in any object, and if the object is to be adequately described, both characteristics are needed [27]. In the case of sugarcane bagasse it is very difficult to measure the shape and size of the various particles that form the clusters, making it particularly difficult to characterize the exact shape and dimensions of the particles.

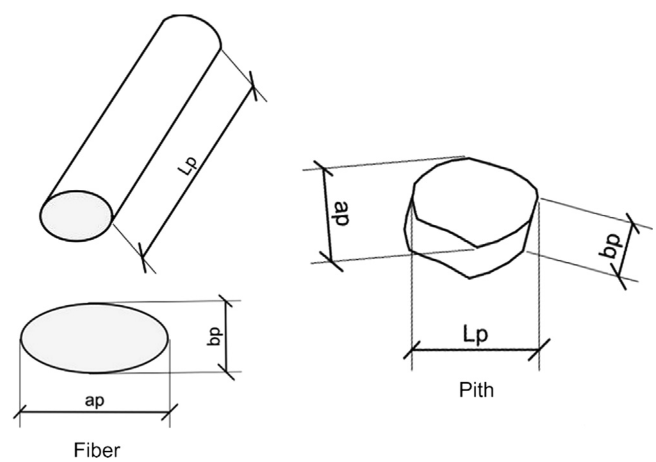

Fig. 9. Geometric characteristics of fibers and pith in sugarcane bagasse [25].

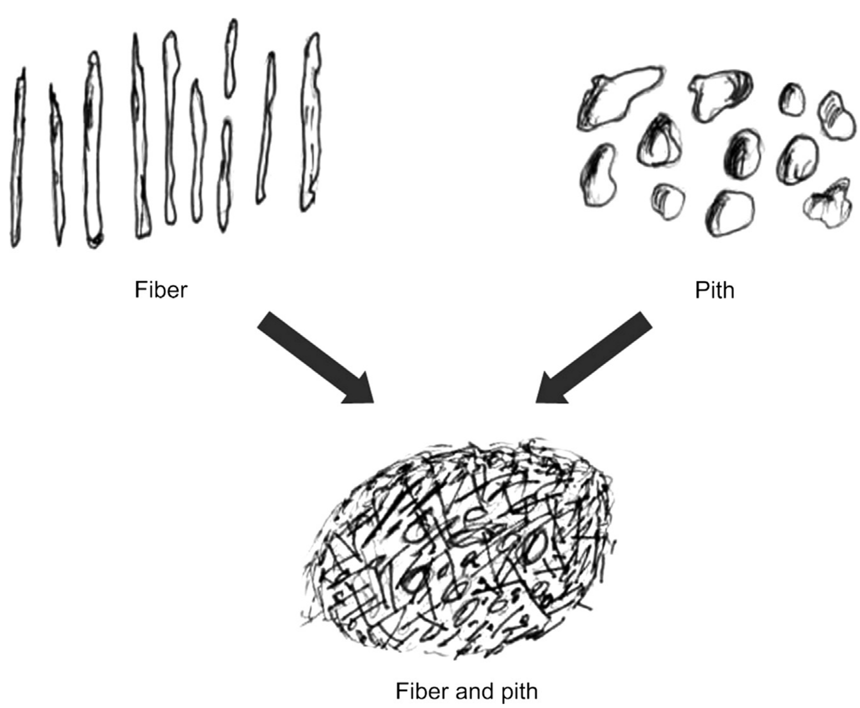

Fig. 8. Fibers, pith particles and clusters of fiber rods and pith of various sizes.

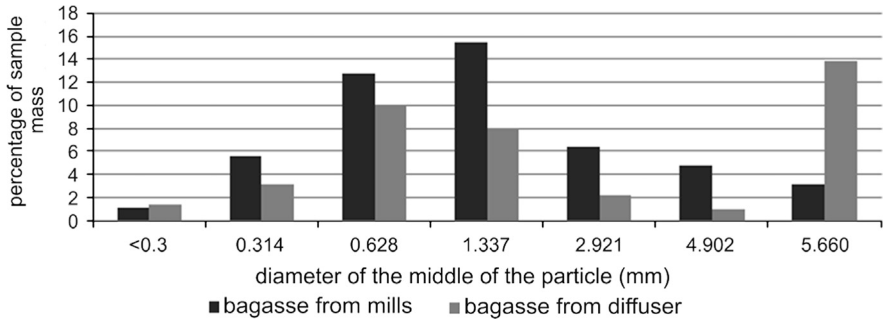

Fig. 10. Particle size distribution for bagasse separated with sieves [26].

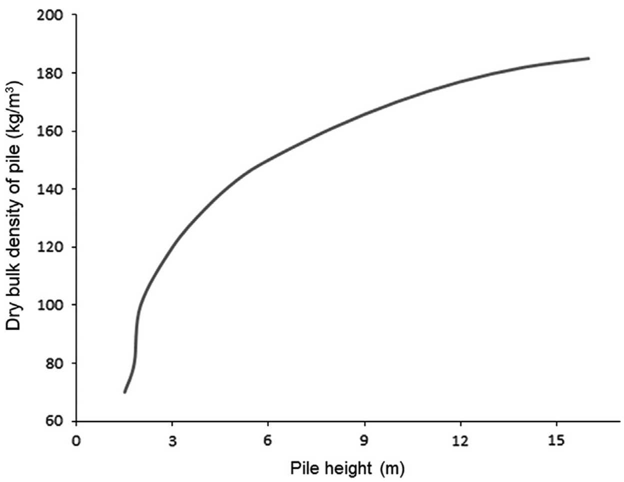

Fig. 11. Bulk density of bagasse against pile height [29].

6.2. The density of bagasse

Biomass density can be expressed in any of three distinct ways depending upon the use to which the figure will be put: bulk density, particle density or actual density.

Bulk density is the ratio of the total mass of a large cluster of particles to the volume occupied by the particles, pores and voids between the particles in kg/m^3.

According to Murry [28] the bulk density of dry and chopped bagasse can vary from 55 to 66 kg/m^3, and Rein [9] reports that if the bagasse is composed of coarse fibers with some compression because of the weight of the fibers, then densities in the order of 75 kg/m^3 or, with finer fibers, up to 90 kg/m^3 are achievable. When moist bagasse is stored in piles several meters high, bulk density can reach up to 200 kg/m^3. Bruin et al. [29] showed that there is a relationship between bulk density and pile height and clearly demonstrated that compression is effective in altering bulk density (Fig. 11).

Particle density is defined as the ratio of the mass of the particles to the volume enclosed by the outer surface of the particles. This parameter is of great importance when studying the fluid dynamics of bagasse particles since volume and mass exert a great influence on the results of any analysis.

One method for measuring density is to use a liquid pycnometer. However, the porosity of the particles and the hygroscopic nature of sugarcane bagasse make this difficult. Rasul et al. [30], using a liquid pycnometer to completely fill the pores in bagasse with water, obtained densities of 220 kg/m^3 for pith, 520 kg/m^3 for fibers and 550 kg/m^3 for skin. Assuming that bagasse is made up of 5% pith, 73% fibers and 22% skin, the resulting average density is 492 kg/m^3. The same authors used a multipycnometer to measure the skeleton density of dry bagasse and obtained a value of 1470 kg/m^3.

6.3. Chemical characterization of bagasse and cane trash

The physical and chemical characteristics of sugarcane bagasse have a direct influence on its use as an energy source. The most commonly used method for power generation is the burning of bagasse in steam generators. A knowledge of the characteristics of bagasse is therefore necessary when designing steam generating equipment.

Gasification and pyrolysis are also used to generate energy from bagasse, and the cellulosic component of bagasse can be hydrolyzed to produce ethanol. Whichever process is used, a knowledge of the characteristics of bagasse is essential when developing the process and designing the equipment.

The characteristics of bagasse depend on several factors, such as the plant species used, the method used to harvest the crop, when it is harvested and the juice extraction process (milling or diffusion), which in turn determines how the bagasse is produced. However, this type of information is seldom available in the literature. Although cane trash is not yet used for power generation, it has great potential for use for this purpose. A knowledge of its characteristics as a fuel is therefore also important.

Bagasse is a complex mixture of cellulose, hemicellulose and lignin that makes up the cell walls of the vascular vessels in sugarcane [9]. The fiber content of stalks depends on the length and diameter of the stalks, and the number of nodes and distance between nodes also influence the amount of fiber obtained in the milling and extraction processes. Extractives and ash complete the typical structure of sugarcane bagasse and other biomasses.

Cellulose is a polymer with a high molecular weight composed largely of glucose units with six carbons in their molecular structures (hexose), whereas hemicellulose is made up mainly of xylose units and small amounts of arabinose, both of which contain five carbons (pentose). Lignin is a complex substance composed mainly of aromatic phenolic compounds, which give sugarcane fiber its rigidity and hardness. The relative amounts of these compounds depend on the variety, age and size of the stalks. Small amounts of inorganic compounds such as silica and calcium are also present in cellular structures in sugarcane, although not in significant quantities in relation to the overall composition of the fiber. Ash is made up of inorganic compounds found in bagasse whose composition depends on the variety of plant, soil type, fertilization method and inorganic materials collected together with the sugarcane when it is harvested (mechanically or manually). The main elements are silica, potassium, calcium, magnesium and phosphorus [5].

Extractives are substances that are not part of the polymeric structure of biomass (cellulose, hemicellulose and lignin) and can be analyzed by extracting them with different solvents such as

water, ethanol and toluene. The main extractive in bagasse is sucrose, which is not completely extracted during the milling and extraction process. Table 3 shows the results of structural analyses of sugarcane bagasse carried out by several authors, as well as the results of an analysis performed as part of this study. With the exception of this study, none of the studies cited in Table 3 analyzed extractives, and the results therefore do not include all the structural components. Table 3 also shows the results of an analysis of cane trash. Analysis for extractives was performed according to the TAPPI 264 cm-97 standard, and analysis of lignin levels according to TAPPI UM 250 and TAPPI 222. Analysis for cellulose and hemicellulose content was performed by hydrolysis with sulfuric acid, with subsequent analysis of total carbohydrate content by HPLC-PAD.

The discrepancies between the results reported by the different authors may stem from the different varieties of sugarcane and different analysis techniques used. There has been interest in cellulose and hemicellulose for the production of second generation ethanol because of their potential for hydrolysis to sugar for subsequent fermentation to ethanol. It is interesting to note in Table 3 that the analysis carried out as part of the present study showed that extractives accounted for 11–15% of total content. As the substance analyzed was sugarcane, some of these extractives may be sucrose.

Table 4 summarizes the results of various elemental analyses of sugarcane bagasse. With the exception of ash content, there is practically no dispersion of the values found, and a generalized average value can be used for the composition of dry ash-free bagasse. The results obtained in this study are also shown in the same table. CHN analysis was performed using a 2400 CHN Elemental Analyzer, S content was performed by optical plasma spectrometry and Cl content was determined by titration.

6.4. Proximate analysis and gross calorific value

Proximate analysis determines the moisture, fixed carbon, volatiles and ash content of a solid fuel. These levels are used to predict the behavior of the fuel during the combustion process. The gross calorific value represents the energy released by complete combustion of the fuel, including the enthalpy of vaporization of the water formed during combustion. For practical applications, it is useful to calculate the lower calorific value, which depends on the moisture present in the fuel and excludes the enthalpy of vaporization of the water formed during combustion and the water in the fuel. Calculation methods are readily available in the basic combustion literature. Table 5 shows the results for the proximate analysis and gross calorific value of bagasse and cane trash; it can be seen that there is limited dispersion of the values reported by the different authors. In the present work the proximate analysis was performed according to the ASTM E-1617-94 and E-1755-01 guidelines, and gross calorific value was determined in accordance with ASTM D-2015.

6.5. Thermogravimetric analysis

Thermogravimetric analysis (TGA) is a useful tool for analyzing the behavior of either residues or solid fuels subjected to a controlled increase in temperature in environments with inert or oxidizing atmospheres [43]. It involves heating a sample of material in a furnace at a controlled temperature (or heating rate) and measuring the reduction in mass of the sample with a precision balance coupled to the furnace. A range of information can be obtained by thermal analysis, including the devolatilization temperature and the temperature at which decarbonization starts.

Figs. 12 and 13 show the thermogravimetric curve (TG) and differential thermogravimetric curve (DTG) for the bagasse and

Table 4
Results of elemental analyses of dry and ash-free sugarcane bagasse and cane trash.

References	Carbon	Hydrogen	Nitrogen	Sulfur	Chlorine	Oxygen
Rein [9]	47.00	5.92	0.33	0.05	n/a	45.81
Camargo et al. [1]	48.33	6.68	–	0.10	n/a	44.88
Van der Poel [35]	47.90	6.40	0.30	0.10	n/a	45.22
Gabra [36]	48.64	5.81	0.21	0.02	0.32	44.98
Jenkins et al. [37]	49.85	6.01	0.16	0.04	0.03	43.89
Turn et al. [38]	49.97	5.88	0.14	0.08	n/a	43.91
Permchart and Couprianov [39]	42.00	6.58	0.26	0.16	n/a	51.00
Filippi [40]	43.77	6.02	0.20	–	n/a	50.00
Manyà and Arauzo [41]	43.60	5.52	0.25	0.07	n/a	50.63
Resende [42]	45.92	6.23	0.38	–	n/a	47.47
Bagasse (this work)	42.61	5.92	0.63	0.12	0.1	50.9
Cane Trash (this work)	42.5	6.02	0.6	0.24	0.44	50.2
Average value	46.01	6.08	0.31	0.1	0.22	47.41

Table 5
Results of different proximate analyses and gross calorific values of bagasse and cane trash reported in this and other studies.

Material	Fixed carbon (daf[a])	Volatile content (daf[a])	Ash (dry basis)	GCV (daf[a]) MJ/kg	Reference
Bagasse	12.94	87.06	n/a	19.24	Rein [9]
Bagasse	13.54	86.45	4.00	19.69	Camargo et al. [1]
Bagasse	12.37	87.62	2.44	19.46	Jenkins et al. [37]
Bagasse	12.26	87.73	3.61	19.19	Turn et al. [38]
Bagasse	9.48	90.5	2.00	19.08	Filippis [40]
Bagasse	12.73	87.26	3.40	18.84	Nassar [34]
Bagasse	19.18	80.81	5.13		Manyà and Arauzo [41]
Bagasse	8.65	91.34	2.93	16.9	Resende [42]
Bagasse	6.93	90.03	2.93	17.72	This work
Cane Trash	10.1	82.25	7.5	17.1	This work

[a] Daf: dry and ash free.

Table 3
Typical structural composition of sugarcane bagasse.

Material	Composition	Cellulose	Lignin	Hemicellulose	Extractives	Reference
Bagasse	Whole	40.0	22.0	33.0	n/a	Purchase[31]
Bagasse	Whole	53.2	22.7	25	n/a	Bernar [32]
	Whole	46.6	20.7	25.2	n/a	
Bagasse	Fiber	47.0	19.5	25.1	n/a	Trina et al. [33]
	Pith	41.2	21.7	26.0	n/a	
Bagasse	Whole	33.6	18.5	29.0	n/a	Nassar et al. [34]
Bagasse	Whole	35.31	22.85	24.01	14.70	This work
Cane Trash	Whole	36.68	20.45	28.57	11.50	This work

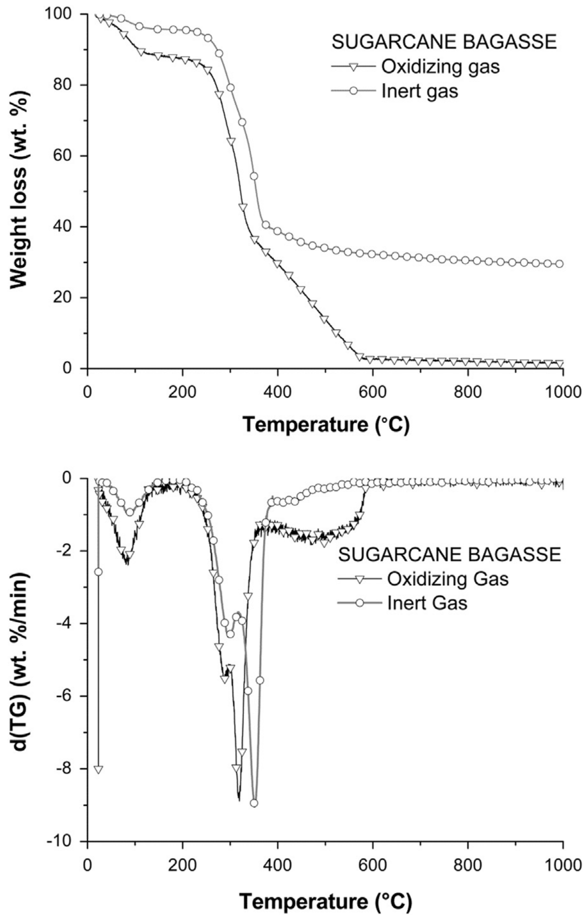

Fig. 12. Thermogravimetric analysis of sugarcane bagasse in an inert oxidizing atmosphere with a heating rate of 10 K/min.

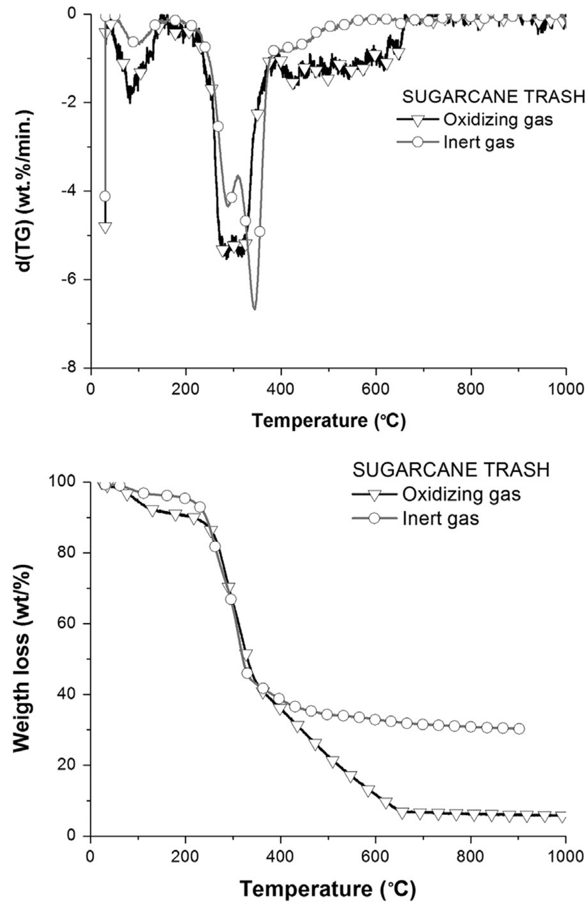

Fig. 13. Thermogravimetric analysis of cane trash in an inert oxidizing atmosphere with a heating rate of 10 K/min.

cane trash samples used here. Devolatilization starts and finishes between 200 °C and 390 °C for sugarcane bagasse and between 180 °C and 390 °C for cane trash with a heating rate of 10 °C/min and an inert atmosphere (argon). Both bagasse and cane trash exhibit two devolatilization peaks at 290 °C and 340 °C, which can be attributed to the decomposition of hemicellulose and cellulose, respectively. These results are similar to those obtained by Ounas et al. [44], Mothé and Miranda [45] and Santos et al. [46]. According to Tognotti et al. [47] and Grotkjaer et al. [48], the ignition temperature of biomasses can be identified by comparing the results of TGA with an inert atmosphere with the results using an oxidizing atmosphere. However, in the present study it was only possible to distinguish the start of fixed carbon combustion at about 400 °C for both cane trash and bagasse. In an oxidizing atmosphere, the DTG curves show that there is a higher rate of mass loss immediately after the beginning of devolatilization, suggesting that the volatiles start to ignite immediately after they are produced, whether in bagasse or cane trash. TGA was performed on a Netzsch model STA-409C analyzer.

6.6. *Analysis of ash*

The properties of interest when analyzing ash are chemical composition and fusibility. These parameters help evaluate the likelihood of refractory materials being attacked or corroding, or the possibility of ash fusing in the combustion system or being deposited on heat-transfer surfaces. It is also important to analyze ash for alkali oxides such as Na_2O and K_2O, which volatilize and condense at temperatures around 760 °C, causing fouling in the cold parts of the steam generators (typically heat-transfer surfaces). Table 6 shows the results of various elemental analyses of bagasse ash as well as the results of elemental analysis carried out using EDS (energy dispersive microanalysis) in a scanning electronic microscope as part of this study.

The amount and composition of inorganic substances in fuel affects the fusibility of ash and is therefore one of the main reasons why molten ash deposits form on heat-transfer surfaces. The properties of ash are defined by its fusibility characteristics, which can be predicted using certain correlations between the chemical composition of the fuel (determined by analysis of the basic and acidic components found in ash in the form of oxides) and the fusion temperature of ash.

A relationship frequently used to analyze the formation of fused ash deposits during the co-combustion of coal and biomass is the correlation between the ratio of the concentration of basic components to the concentration of acidic components $R_{(B/A)}$ in ash and the behavior of the fusibility of ash [49]. The values for this ratio can be classified into two bands chosen to estimate the risk of deposits forming: $R_{(B/A)} < 0.75$, for which the risk of ash deposits forming is lower, and $R_{(B/A)} > 0.75$, for which the risk is higher, indicating that the greater the concentration of basic components, the greater the risk of fused ash deposits. Other indexes have been proposed to predict the fusibility behavior of ash, and these also relate the components found in ash to its proprieties. One such indicator, which is frequently used to predict ash deposits and fouling, is an alkali index [50]. This expresses the alkali oxide content in a fuel per unit of energy. The authors suggest that above 0.17 kg alkalis/GJ, fouling is likely to occur and that above 0.34 kg alkali/GJ it is certain to occur. Table 7 shows the ash fusibility indexes calculated for the various ash compositions shown in Table 6.

Table 6
Elemental composition of bagasse and cane trash ash.

Oxides/References	Rein [9]	Camargo et al. [1]	Jenkins et al. [37]	Turn et al. [38]	Gabra [36]	Manyà [41]	Bagasse (this work)	Cane Trash (this work)
SiO_2	75.20	46.00	46.61	41.87	72.30	64.29	43.01	40.81
Al_2O_3	2.70	2.80	17.69	22.25	8.00	3.44	7.0	9.64
Fe_3O_3	2.60	3.00	14.14	20.90	6.20	3.69	5.23	4.47
Ti_3O_2	0.01	0.53	2.63	3.87	0.60	1.25	1.56	1.17
P_2O_5	1.46	–	2.72	1.13	0.90	2.89	5.82	1.77
CaO	6.90	5.40	4.47	3.50	4.20	4.84	12.75	21.15
MgO	1.70	0.79	3.33	1.45	2.30	1.33	6.70	4.49
Na_2O	0.60	0.50	0.79	0.26	1.00	0.31	0.20	0.54
K_2O	5.10	23.00	0.15	2.59	4.50	14.34	14.14	8.03
SO_3	2.70	–	2.08	0.90	–	0.97	1.68	4.62
MnO_2	0.02	7.30	3.33	–	0.10	0.54	0.53	0.68
Others	0.92	10.55	2.06	1.28	0.10	1.41	1.35	2.58
Total	99.91	100	100	100	100	100	100	99.95
Ash	2.00	4.00	2.44	3.61	7.40	5.02	2.93	7.50

All the data for bagasse, except for cane trash as indicated.

Table 7
Fusibility index and alkali index for bagasse and cane trash.

Parameters	Rein [9]	Camargo et al.[1]	Jenkins et al. [37]	Turn et al. [38]	Gabra [36]	Manyà [41]	Bagasse (this work)	Cane Trash (this work)
$R_{(B/A)}$	0.14	0.19	0.34	0.4	0.16	0.15	0.87	0.78
Probability of deposit formation	Low	Low	Low	Low	Low	Low	High	High
A.I.	0.61	4.97	0.12	0.56	2.26	3.98	2.30	3.48
Probability of deposit formation	High	High	low	High	High	High	High	High

All the data for bagasse, except for cane trash as indicated.

Table 8
Ash softening temperature °C [1].

Oxidizing atmosphere	
Initial temperature	960
Final temperature	1235
Reducing atmosphere	
Initial temperature	915
Final temperature	1130

The results indicate that there was no consistency between the two methods used in 66% of the analyses cited in this paper. There was a high probability of deposit formation in all the bagasse and cane trash samples analyzed here regardless of the index used in the calculations. Table 8 shows the results of an analysis of the softening temperature of ash; it can be seen that in the study from which these data were taken, bagasse ash starts to soften at temperatures below 1000 °C. As this is the typical temperature of gases leaving the combustion chamber in bagasse boilers, ash fouling on the heat transfer surfaces of boilers can be expected. In fact, bagasse steam generators frequently use cleaning devices known as soot blowers.

These findings suggest that further research into the fusibility of cane trash ash is needed.

7. Analysis of energy consumption during bio-ethanol production

The amount of energy used and the extent to which process residues (bagasse) are used in bio-ethanol production depend on the production techniques used, the type of products and the efficiency of the equipment. Most sugarcane mills in Brazil produce both sugar and ethanol and have sufficient flexibility in their production processes to meet the demand for either product or to produce the product with the best market price in a particular year. There are also a number of mills that produce only ethanol. These are the focus of this article, which seeks to analyze the use of residues in the production of sugarcane biofuel. The energy balance for a sugar and ethanol mill depends on the proportions of sugar and ethanol produced, as both processes have slightly different energy demands.

7.1. The ethanol production process

The production of ethanol from sugarcane can be divided into the following steps:

- preparation and milling of the cane to extract the juice;
- preparation of juice for the fermentation process;
- fermentation of mash to produce ethanol;
- distillation of wine to recover the ethanol produced during fermentation.

These processes can vary depending on the equipment used and the energy integration between the various stages. Fig. 14 shows a process flow diagram of a typical medium-sized plant (500 tc/h).

Table 9 shows the process stream and inflow properties at each stage in the production process.

The vast majority of sugarcane mills in Brazil produce their own electricity to meet the demands of their electrical equipment and administration buildings. This power is supplied by a co-generation system, in which bagasse is the fuel for a thermal steam cycle. The superheated steam produced is then expanded in back-pressure turbines. The exhaust steam expanded in the turbine is used as a source of thermal energy during ethanol production. The turbines drive the milling tandem, the pumps supplying water to the steam generators and some of the high-capacity processing pumps. Mills that meet all their own needs for

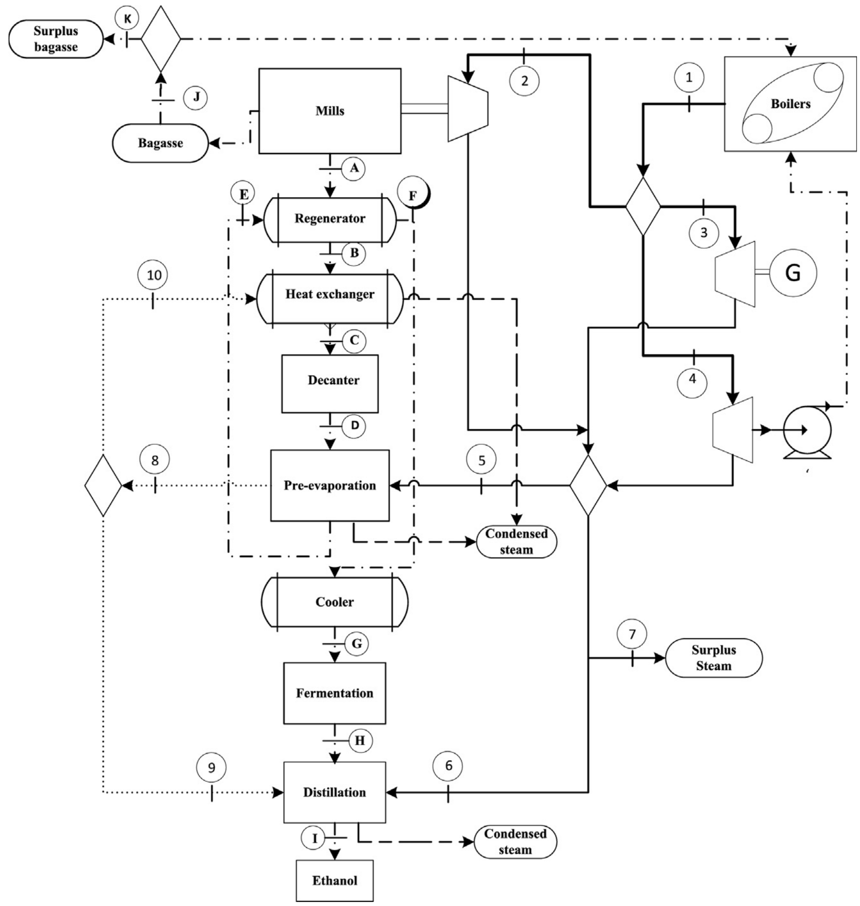

Fig. 14. Flowchart of a typical sugarcane-to-ethanol mill and the energy co-generation system.

electricity generate steam with pressures from 20 to 25 bar and temperatures from 300 °C to 360°C. In 2001, mills operating within these parameters represented 92.4% of mills installed in the state of São Paulo [51]. Newer facilities have adopted higher pressures and steam temperatures to increase surplus electricity production.

7.2. Preparation and milling of sugarcane

For details of this process and specific variations refer to item 5.

7.3. Preparation of juice for the fermentation process

For the fermentation process, the sucrose concentration in the juice is adjusted to suitable levels (typically in the order of 8–9% of sugar content), and impurity levels are reduced, usually by decantation and adjustment of the temperature to around 32 °C. When the juice leaves the milling tandem it is heated to 105 °C as it passes through a regenerator and juice vapor heater. In the regenerator, the cold juice exchanges heat with the juice that has already been treated and is at 115 °C. Juice vapor is the steam generated from juice in the pre-evaporator. After the steam heater, the juice proceeds to the clarifier, where decantation occurs, usually with the addition of lime. Then it proceeds to the pre-evaporator, where the sugar concentration is adjusted. The juice is then cooled to 32 °C by passing through the regenerator and a water cooler, after which it is sent to the fermentation process.

Thermal energy is required at this stage because of the pre-evaporation of excess water from the juice. This pre-evaporation produces steam, which is known as juice vapor and is used as heating steam in the following juice-evaporation and distillation stages.

7.4. Fermentation

Fermentation is the biological process that transforms the sugar in juice into ethanol, carbon dioxide and other residual compounds, the latter in very low concentrations. It can be a continuous process or can be performed in batches. It is carried out at temperatures close to room temperature, and the heat generated during the process means that a cooling system is needed to cool the juice. Therefore, there is no demand for thermal energy during this stage of the production process.

7.5. Distillation

In the distillation process ethanol is separated from fermented juice. Hydrous ethanol (96°GL) or anhydrous ethanol (99°GL) can be produced. Production of the former typically involves two distillation stages, while production of the latter requires an additional stage because of the azeotropic properties of a water-ethanol mixture. Energy is provided by exhaust steam and may sometimes be supplemented by juice vapor, when available, or medium-pressure steam (10 bar) if necessary. The energy consumption values given in this paper relate to the production of hydrated ethanol, the biofuel used in Otto-cycle vehicles in Brazil.

7.6. Steam production

Steam is the main source of energy in a sugarcane ethanol mill. Superheated steam is produced by combustion of bagasse from the milling tandem. It is expanded in back-pressure turbines, which drive the milling tandem, steam generator water supply pumps, high-flow process pumps and electricity generators. The exhaust

Table 9
Inflow properties for each stage in the flow diagram.

Identification	Process stream	Flow rate [kg/tc]	Temperature [°C]	Pressure [bar]	Concent-ration
A	Sugarcane juice	959	42	–	14[a]
B	Sugarcane juice	959	72.2	–	14[a]
C	Sugarcane juice	959	105	–	14[a]
D	Clarified juice	875	96	–	14[a]
E	Pre-evaporator juice	675	115	–	18.5[a]
F	Pre-evaporator juice	675	72.2	–	18.5[a]
G	Mash	675	32	–	18.5[a]
H	Wine	734	–	–	8.3[b]
I	Ethanol	63.2	–	–	99[b]
J	Bagasse	250	–	–	–
K	Surplus bagasse	27.6	–	–	–
1	High pressure Steam	480	320	22	–
2	High pressure Steam	280	320	22	–
3	High pressure Steam	161.4	320	22	–
4	High pressure Steam	38.9	320	22	–
5	Expansion Steam	245.3	130	2.5	–
6	Expansion Steam	90.4	130	2.5	–
7	Expansion Steam	144.6	130	2.5	–
8	Juice vapor	218.4	115	1.0	–
9	Juice vapor	162.8	115	1.0	–
10	Juice vapor	55.6	115	1.0	–

[a] kg sucrose/kg sugarcane juice.
[b] kg ethanol/kg sugarcane juice.

Table 10
Energy required to produce mechanical work in a typical mill, steam 22 bar/320 °C.

Equipment	Specific consumption (MJ/tc)	Conversion efficiency (%)	Steam consumption (kg/tc)	% Steam consumption
Mills	54	55	280	58.3
Turbo pumps	6.14	45	38.9	8.1
Turbo generator	39.6	70	161.4	33.6
Total			480.3	100

steam from the turbine supplies the thermal energy required for the ethanol production process. The electrical energy produced is usually sufficient for the electrical requirements of the mill and any excess is sold.

7.7. Energy consumption

An estimate of the energy needed to produce the mechanical work required in a typical mill was determined from operating parameters collected during visits to five typical medium-sized mills located in the state of São Paulo. The parameters were the specific work required for the milling tandem, turbo pumps and electrical power generation and the conversion efficiencies, including the isentropic efficiency of the steam turbines and the efficiency of the mechanical drives. The specific energy consumption of the milling tandem (shredders and mills) was calculated to be 54 MJ/tc, which is consistent with values reported by other authors [52], as is the conversion efficiency of 55% for back-pressure turbines with powers from 500 kW to 1500 kW. The feedwater pumps for the steam generators and some process pumps are also driven by turbines, which have specific energy consumptions of 6.14 MJ/tc and drive efficiencies of around 45% [1]. The specific electricity consumption of the mills surveyed was approximately 39.6 MJ/tc, which is consistent with data reported in the literature [52,53]. For turbines with power ratings in the order of 5000 kW, conversion efficiency was 70%. Table 10 shows the results calculated based on processing of one tonne of raw cane.

Table 11
Thermal energy consumption during the production of ethanol (saturated steam at 2.5 bar).

Stage	Exhaust steam (kg/tc)	First-effect juice vapor (kg/tc)	Process steam total (kg/tc)	(%) Steam consumption
Heater		55.6	55.6	10
Pre-evaporator	245.3		245.3	44.3
Distillation	90.4	162.8	253.2	45.7
Total	335.7	218.4	554.1	100

About 58% of all the steam produced is used to drive the milling tandems, the most energy-intensive operation in sugarcane processing.

Thermal energy consumption was also calculated based on the flowchart in Fig. 14. Thermal energy is used during the preparation of juice and during pre-evaporation and distillation. The steam requirement was calculated based on typical processing conditions (temperature and sugar concentration) and an assumed distillery steam consumption of 4.0 kg steam/kg of hydrous ethanol produced [1]. This figure was also confirmed during visits to mills. For anhydrous ethanol production there is an additional consumption of 0.48 kg steam/kg of ethanol because of the rectification column. The results are shown in Table 11.

According to Table 11, total consumption of process steam is greater than the amount of exhaust steam produced in the turbines. However, the use of energy integration, with first-effect juice vapor and heat regeneration, results in a steam surplus of in the order of 145 kg/tc (the difference between the exhaust steam produced and the exhaust steam used – 480 kg and 335 kg, respectively). In mills that also produce sugar, this surplus is sent to the sugar concentrators, as the specific steam consumption for sugar production is usually higher than for ethanol production [52]. Because of the greater availability of exhaust steam in distilleries that only produce ethanol, some of the juice vapor does not need to be used in the distillation process and is either cooled or discarded.

Table 12 shows typical parameters for steam generation and consumption of sugarcane bagasse. Fiber content varies throughout the harvest because different types of cane are used and because the cane is harvested up to 5 years after it has been planted. Any variation in fiber content, however, is limited to 12–14%, so that there is only a slight variation in the amount of bagasse per tonne of cane during the harvest period. The parameters defining the ethanol productivity index in a mill are related to fermentation yield, alcohol content and distillation yield. The typical ethanol productivity index is 80 L/tc.

Bagasse boilers have efficiencies of around 80%. Most of the power loss is associated with a loss of enthalpy in combustion gases and unburned fuel in ash. The bagasse goes straight from the milling tandem to the boilers and has an average wet basis moisture content of 50%. This high moisture content requires operation with a large amount of excess air and the use of preheated air from heat recovery systems or steam preheaters. The thermal efficiency of co-generation plant in a typical mill (defined as the ratio of useful thermal energy produced to the quantity of fuel used) is in the region of 70%. The electrical generating efficiency of mills that do not produce surplus electricity is around 6%. The bagasse produced is more than sufficient to meet all the energy needs of the mill, as about 15% is surplus.

Table 12
Ethanol production, steam generation and co-generation parameters in a typical sugarcane-to-ethanol plant.

Stage	Parameters	Units	Calculated	Average
Process	Fiber content in sugarcane	%	12.5	12–14 [21]
	Bagasse Production (wet basis)	kg/tc	250	200–280 [21]
	Ethanol Production Index	L/tc	80	60–85, [57]
	Steam consumption in the mill	kg/tc	480	370–410 ([56]
Steam generation	Bagasse consumption in the boiler	kg/tc	211.6	
	Surplus bagasse	kg/tc	38.4	Corresponding to 15.3%
	Efficiency of the steam generator	%	80	
	Specific steam production	kg steam/kg wet bagasse	2.27	
Co-generation	Efficiency of thermal co-generation	%	69.5	
	Efficiency of work co-generation	%	6.3	
	Co-generation efficiency (thermal+work)	%	75.8	

There is considerable scope for improving the efficiency of conventional ethanol-producing mills in terms of their use of the energy in residues (bagasse and cane trash). Various studies have analyzed and proposed new systems as well as greater energy integration to reduce energy consumption and increase energy efficiency [54,55,52]. Conversion efficiencies in the production of mechanical work are low because small back-pressure turbines are used. In the production process, distillation accounts for the greatest consumption of thermal energy but has the potential for significant improvements in terms of steam consumption. Although sugarcane trash is not yet used as an energy source, it is produced in similar quantities to bagasse (around 140 kg/tc) and has lower moisture contents (15–25%) [21].

8. Conclusions

This paper has described and analyzed how residues (bagasse and cane trash) are produced from sugarcane and their use as an energy source in the production of ethanol. The morphology of the sugarcane plant was described, and details were given of the processes by which bagasse and cane trash are produced.

Bagasse is what is left after sugarcane stalks have been shredded and the sucrose-rich juice extracted either by milling to open the cane cells or by diffusion in a heated aqueous environment. Both processes make use of tandem mills.

Cane trash is a by-product of the mechanical harvesting of sugarcane. Although it is usually left in the fields, several studies have been carried out to determine the best way for it to be collected and taken to a mill. Cane trash and bagasse have similar yields and represent an important untapped energy source.

The characteristics of both of these residues that make them suitable for use as fuel were described, and the results of various analyses in the literature were presented. Bagasse and cane trash have similar fuel characteristics to other biomasses fuels. Special attention should be given to the characteristics of cane trash ash, which has higher fusibility and alkali levels than bagasse. Further studies are therefore required on the use of cane trash as a fuel in conventional steam generators.

The use of sugarcane bagasse as an energy source for ethanol production was also analyzed. A flowchart of a typical mill was described and the thermal and mechanical energy consumption at various stages of the production process was determined. Of the energy consumed as work, about 58% is accounted for by milling and juice extraction, and 33% by the generation of electricity for use in the plant. Around 45% of the thermal energy is used in the distillation of ethanol and 44% in the preparation of juice for fermentation. In a typical mill using steam generators operating at average pressure and temperature (22 bar, 300–360 °C), about 15% of the bagasse produced is surplus, and an average of 480 kg of steam is used per tonne of cane processed. Mills with these characteristics is rarely designed for producing surplus electricity.

An energy consumption analysis revealed that there was significant scope for reducing the amount of steam needed to operate the turbines in mills because of the low isentropic efficiencies identified. There is further scope for reducing steam consumption in the distillation stage, which typically uses about 4 kg of steam per liter of ethanol produced.

Cane trash, which is not yet used for energy production, also shows great energy potential because it is produced in similar quantities to bagasse, and its calorific value is only slightly lower.

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